

Habitable Planets Around White and Brown Dwarfs: The Perils of a Cooling Primary

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ABSTRACT

White and brown dwarfs are astrophysical objects that are bright enough to support an insolation habitable zone (IHZ). Unlike hydrogen-burning stars, they cool and become less luminous with time, and hence their IHZ moves in with time. The inner edge of the IHZ is defined as the orbital radius at which a planet may enter a moist or runaway greenhouse, phenomena that can remove a planet's surface water forever. Thus, as the IHZ moves in, planets that enter it may no longer have any water, and are still uninhabitable. Additionally, the close proximity of the IHZ to the primary leads to concern that tidal heating may also be strong enough to trigger a runaway greenhouse, even for orbital eccentricities as small as 10^{-6} . Water loss occurs due to photolysis by UV photons in the planetary stratosphere, followed by hydrogen escape. Young white dwarfs emit a large amount of these photons as their surface temperatures are over 10^4 K. The situation is less clear for brown dwarfs, as observational data do not constrain their early activity and UV emission very well. Nonetheless, both types of planets are at risk of never achieving habitable conditions, but planets orbiting white dwarfs may be less likely to sustain life than those orbiting brown dwarfs. We consider the future habitability of the planet candidates KOI 55.01 and 55.02 in these terms and find they are unlikely to become habitable.

1. Introduction

The search for extrasolar life begins with the search for liquid water. All life on Earth requires liquid water and hence it is reasonable to surmise that life beyond the Earth is

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also sustained by it. Most campaigns to search for life have focused on the habitable zone (HZ) of hydrogen burning “main sequence” (MS) stars that are similar to the Sun. However recent studies have begun to explore the possibility of habitable planets around brown dwarfs (BD) (Andreeshchev & Scalo 2004; Bolmont et al. 2011) and white dwarfs (WD) (Monteiro 2010; Agol 2011b; Fossati et al. 2012). Furthermore, as these objects are relatively small and dim, transits are more readily detectable than for MS stars (Blake et al. 2008; Faedi et al. 2009; Di Stefano et al. 2010; Agol 2011b). In this investigation we consider the evolution of the HZs of these objects in the context of tidal heating and the evolution of the primary’s luminosity and spectral energy distribution.

WDs are the remnants of stars that have burned all the hydrogen in their cores into helium. As the hydrogen burning ends, the core begins to fuse the helium atoms and becomes hotter. This extra heat blows the envelope away, leaving just the core. Most WDs are about the size of the Earth, but have a mass of $\sim 0.6 M_{\text{Sun}}$ and a luminosity of $\sim 10^{-3} L_{\text{Sun}}$ (Bergeron et al. 2001). However, a range exists, and the luminosity actually evolves over several orders of magnitude.

BDs are objects that are not massive enough to produce the central pressures necessary to fuse hydrogen into helium. Nonetheless, BDs can support an HZ as their slow contraction converts gravitational energy into heat (Burrows et al. 1997; Baraffe et al. 2003). The habitability of planets about BDs has received less attention than habitability of planets orbiting hydrogen-burning stars, as a) relatively few are known, b) it is unknown if planets can form around them, and c) they are very faint. However, new surveys, such as that of the WISE spacecraft, have found hundreds of these objects (Mainzer et al. 2011; Kirkpatrick et al. 2011), opening the possibility of detecting planets in orbit around BDs.

Although no terrestrial planets are currently known to orbit either a WD or a BD, there is no reason to believe they do not exist. Giant planets have been detected, such as a $\sim 5 M_{\text{Jup}}$ planetary companion ~ 55 AU from a nearby BD (Chauvin et al. 2005). Subsequent observations have confirmed this object is a companion to the BD (Song et al. 2006), but its colors and luminosity still pose a challenge to accurately estimating its mass (*e.g.* Gizis et al. 2007; Skemer et al. 2011). Mullally et al. (2008) used the periodicity in arrival times of pulsations of one white dwarf, GD66, to infer the presence of a $2.4 M_{\text{Jup}}$ object at 4.5 AU. Follow-up observations have only placed upper limits on the companion’s mass, leaving its planetary status ambiguous (Mullally et al. 2009; Farihi et al. 2012). Additional giant planets on wide orbits have also been detected around the evolved (post-MS) stars NN Serpentis (Beuermann et al. 2010; Horner et al. 2012), DP Leonis (Beuermann et al. 2011), and HW Virginis (Beuermann et al. 2012).

Furthermore, there is ample evidence for protoplanetary disks that could transform

into terrestrial planets. BDs have been observed to host protoplanetary disks that could form planets (Jayawardhana et al. 2003; Apai et al. 2005). Some WDs host metal-rich disks (Gänsicke et al. 2006), and others appear to have been polluted with metals or water, possibly from tidally-disrupted planets or asteroids (Jura 2003; Jura & Xu 2012). While the post-MS evolution is a challenging barrier to the survival of close-in planetary companions to WDs (see *e.g.* Nordhaus et al. 2010), some or all of the rocky core may survive engulfment, or planets may form from the debris of the stellar envelope. For example, two terrestrial planet candidates have recently been discovered orbiting Kepler Object of Interest (KOI) 55, a $\sim 0.5 M_{\text{Sun}}$ “extreme horizontal branch” star that will likely become a WD (Charpinet et al. 2011). Thus, we assume that water-rich terrestrial planets can exist around these objects.

Previous work on BD and WD HZs (Andreeshchev & Scalo 2004; Monteiro 2010; Agol 2011b; Bolmont et al. 2011) determined orbits for which the radiation flux of the primary is equal to the flux limits found for MS stars (Kasting et al. 1993; Selsis et al. 2007; Barnes et al. 2008). The identification of this so-called insolation habitable zone (IHZ) is an important first step in constraining the possibility of habitable planets orbiting WDs and BDs, but one cannot neglect how a planet behaves prior to the arrival of the IHZ at its orbit. The inner edge of the HZ is defined to be the orbits at which a desiccating greenhouse, either moist, runaway or tidal, is just possible (Kasting et al. 1993; Barnes et al. 2012). These phenomena may ultimately remove all surface water and leave an uninhabitable planet behind. Thus, planets initially interior to the HZ may not actually be habitable after the primary has cooled and/or tidal heating has subsided sufficiently for the planet to reside in it. Note that we will refer to the HZ as resulting from both irradiation and tidal heating, but to the IHZ as the classic habitability model of *e.g.* Kasting et al. (1993).

For desiccation to occur, a multi-step process must transpire. First, the surface flux must reach a critical value F_{crit} , which is typically around 300 W m^{-2} (Kasting et al. 1993; Abe 1993; Selsis et al. 2007; Pierrehumbert 2010). At this level, water may either escape the troposphere, and/or become opaque to infrared radiation. In both cases, water vapor in the stratosphere can then be photolyzed by high energy radiation. Then, the freed hydrogen atoms may escape to space (Watson et al. 1981). Without the hydrogen to bond with oxygen, the planet has no water and is not habitable. Extrapolating from the Solar System, such planets will be Venus-like with large CO_2 -dominated atmospheres. Thus, in order to become sterile, the planet must also be bathed in high energy radiation for a long enough time for all the hydrogen to be lost. Barnes et al. (2012) argued for a desiccation timescale, t_{des} of 10^8 years for low mass stars. The situation is more complicated here as BDs and WDs are very different objects and we discuss this point in detail in § 2.

The relatively low luminosities of WDs and BDs place their IHZs very close to the primary, ~ 0.01 AU. At these distances tidal effects are important, and tidal heating may provide enough surface energy to drive a runaway greenhouse (Barnes et al. 2012). Therefore planets orbiting WDs and BDs must also avoid desiccation via the “tidal greenhouse.” As planetary tidal heating scales with primary mass, WDs can tidally heat planets more effectively than BDs, all other things being equal.

Beyond identifying planets in danger of desiccation, we also explore the diversity of terrestrial exoplanets orbiting WDs and BDs. In and around the IHZ, radiative and tidal heating will produce a mix of planetary properties, as heating fluxes can be lower than F_{crit} . For example, some planets in the IHZ may only be tidally heated as much as Io (Jackson et al. 2008; Barnes et al. 2009a; Heller et al. 2011). Therefore, if planets are found around these objects, and within the IHZ, they may be categorized based on the strengths of tidal and radiative heating. We find a wide array is possible, including several types of Venus-like planets, and some exotic types of habitable planets that do not exist in the Solar System.

Bolmont et al. (2011) considered the tidal evolution of the orbits of planets around BDs, but largely ignored tidal heating. The orbital evolution can be quite complicated as some orbits will shrink while others expand, depending on the spin period of the BD and the orbital semi-major axis. They found that planets may spend a short amount of time in the IHZ due to tidal evolution. In this study, we examine how the cooling of the primary and the tidal heating of a planet orbiting a WD or BD affect the likelihood of habitability. We find that the radiation environment prior to arrival in the IHZ is at least as important as the orbital evolution.

This paper is organized as follows. In § 2, we outline models for primary cooling, the IHZ, tidal heating, hydrogen loss, and describe a planetary classification scheme based on tidal and radiative heating. In § 3, we examine planets orbiting WDs. In § 4 we turn to BDs. Finally, in § 5, we draw conclusions.

2. Methodology

This study relies heavily on results from Barnes et al. (2012), Agol (2011b), and Bolmont et al. (2011). We first describe the cooling properties of WDs and BDs and the IHZ. Next we combine them to show how the IHZs evolve with time. We briefly review tidal phenomena but do not repeat all the equations here, as they are presented in their entirety in (Barnes et al. 2012, App. D). Finally, we describe a planetary classification scheme that categorizes planets

based on their insolation and tidal heat flux at the surface.

2.1. White Dwarf Cooling

Most WDs have masses near $0.65 M_{\text{Sun}}$ with a dispersion of $0.2 M_{\text{Sun}}$ (Bergeron et al. 2001). Agol (2011b) focused on $0.6 M_{\text{Sun}}$ WDs, so we do the same here. Bergeron et al. (2001) compute masses, ages and effective temperature for 152 white dwarfs using theoretical models and we excised all WDs with masses $< 0.55 M_{\text{Sun}}$ and $> 0.65 M_{\text{Sun}}$ from their Table 2 and plot the remaining 41 objects as stars in Fig. 1.

Next we fit a third-order polynomial to the data (assuming uniform uncertainties per point) in order to produce a WD cooling function. If L is the base-10 logarithm luminosity in solar units and t the time in Gyr, then we find

$$L = -2.478 - 0.7505t + 0.1199t^2 - 6.686 \times 10^{-3}t^3. \quad (1)$$

WDs cool rapidly for about 3 Gyr, then level off before falling off again at about 7 Gyr. The relatively constant luminosity from 3 – 7 Gyr is probably due to the crystallization of the degenerate core (Salpeter 1961; Segretain et al. 1994; Hernanz et al. 1994; Metcalfe et al. 2004). Note that the age given on the abscissa of Fig. 1 is the WD cooling time only. It does not include the pre-WD age of the former main-sequence star, so we neglect the pre-WD circumstances of the system.

2.2. Brown Dwarf Cooling

BDs are objects that burn deuterium, but not hydrogen, and are thus less luminous than MS stars. Traditionally, BDs are assumed to have masses in the range $13 - 80 M_{\text{Jup}}$, but the actual limits are more complicated (see Spiegel et al. 2011, for a review). Most of their luminosity results from the release of gravitational energy via contraction. As relatively few BDs are known and ages are difficult to constrain empirically, we rely on theoretical models to determine their luminosity L_{BD} and effective temperature T_{eff} . Two standard models are available (Burrows et al. 1997; Baraffe et al. 2003) and their results are shown in Fig. 2. The two models agree with each other, and we use Baraffe et al. (2003) in order to be consistent with Bolmont et al. (2011).

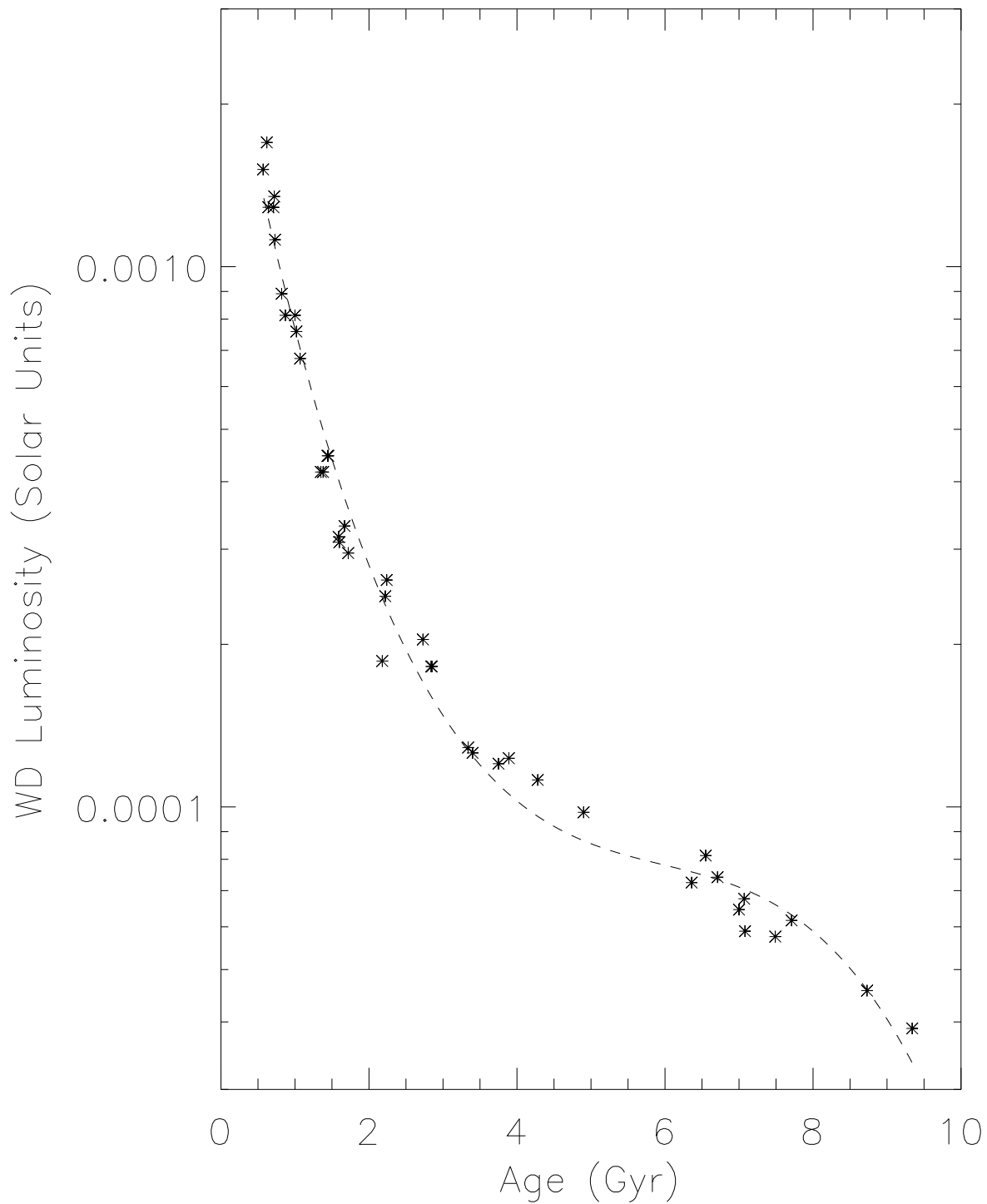


Fig. 1.— Luminosity as a function of cooling time for the WDs in the Bergeron et al. (2001) survey with masses $0.55 \leq M_* \leq 0.65 M_{\text{Sun}}$ (stars), and the analytic fit of Eq. (1) (dashed curve).

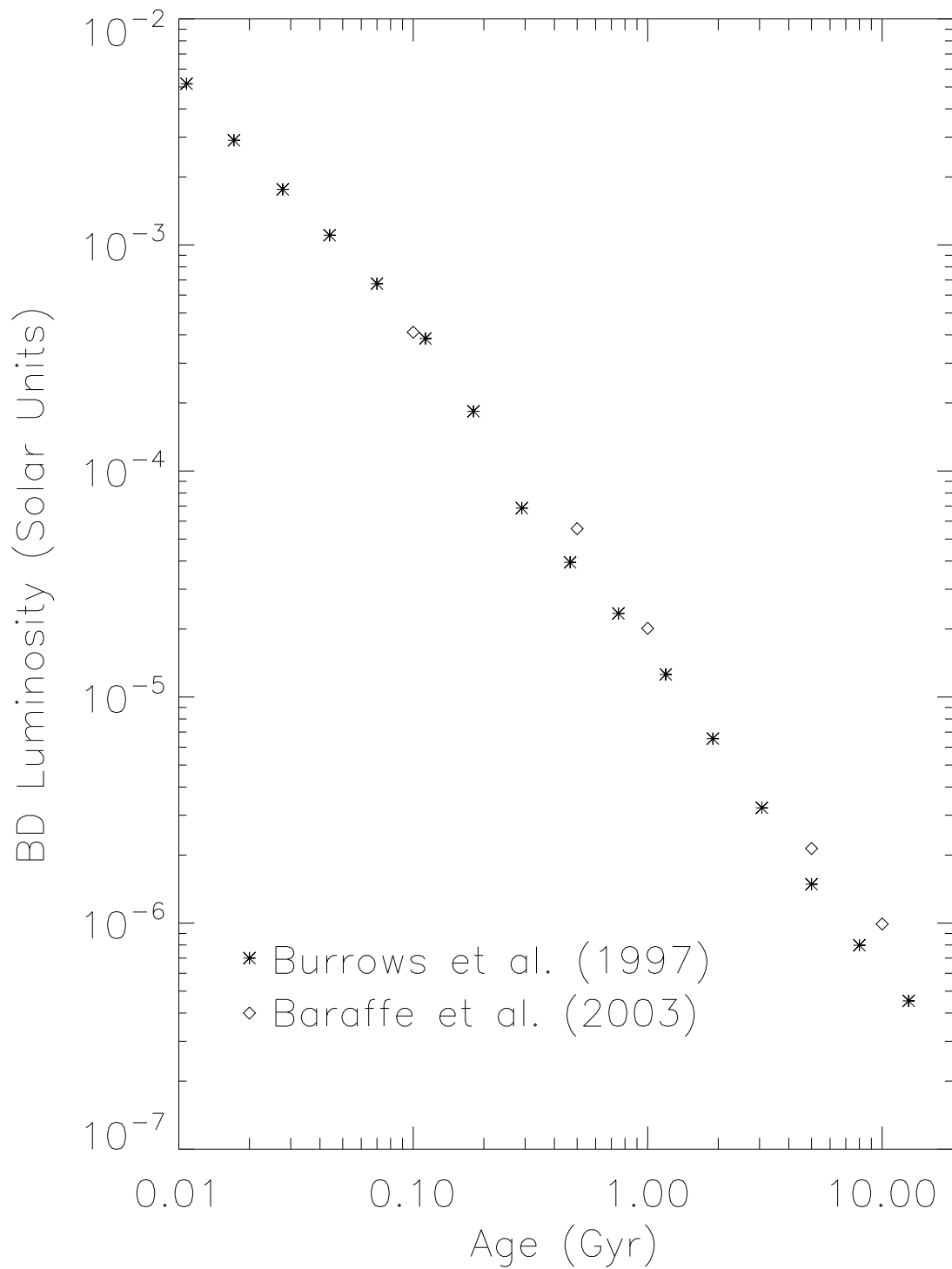


Fig. 2.— Luminosity as a function of time for a 42 Jupiter mass BD according to Burrows et al. (1997) (stars) and Baraffe et al. (2003) (diamonds).

2.3. The Insolation Habitable Zone

We follow exactly the assumptions, models and symbols presented in Barnes et al. (2012). We label the locus of orbits for which starlight can provide the appropriate level of energy for surface water the IHZ. We use the Barnes et al. (2008) IHZ that merges the work of Selsis et al. (2007) and Williams & Pollard (2002) in order to estimate IHZ boundaries for eccentric orbits and ignore the role of obliquity (*c.f.* Dressing et al. 2010)

With the previous assumptions, the inner edge of the IHZ is located at

$$l_{in} = (l_{in\odot} - a_{in}T_* - b_{in}T_*^2) \left(\frac{L_*}{L_\odot} \right)^{1/2} (1 - e^2)^{-1/4}, \quad (2)$$

and the outer edge at

$$l_{out} = (l_{out\odot} - a_{out}T_* - b_{out}T_*^2) \left(\frac{L_*}{L_\odot} \right)^{1/2} (1 - e^2)^{-1/4}. \quad (3)$$

In these equations l_{in} and l_{out} are the inner and outer edges of the IHZ, respectively, in AU, $l_{in\odot}$ and $l_{out\odot}$ are the inner and outer edges of the IHZ in the solar system, respectively, in AU, $a_{in} = 2.7619 \times 10^{-5}$ AU/K, $b_{in} = 3.8095 \times 10^{-9}$ AU/K², $a_{out} = 1.3786 \times 10^{-4}$ AU/K, and $b_{out} = 1.4286 \times 10^{-9}$ AU/K² are empirically determined constants, and L_* and L_\odot are the primary’s and solar luminosity, respectively. $T_* = T_{eff} - 5700$ K, where T_{eff} is the “effective temperature” of the primary

$$T_{eff} = \left(\frac{L_*}{4\pi\sigma R_*^2} \right)^{1/4}, \quad (4)$$

where R_* is the primary’s radius.

We can combine the cooling rates with the IHZ models to determine how the position of the IHZ evolves with time. In Fig. 3 we show the location of the IHZs in time for the 0.06 M_{Sun} WD and 40 M_{Jup} BD cases described previously. Initially the BD’s IHZ is only a factor of 2 closer in than the WD’s, but for ages greater than 1 Gyr, the BD IHZ is about order of magnitude closer to the host.

2.4. Spectral energy distributions of white dwarfs and brown dwarfs

Not only will the luminosities of cooling WDs and BDs change, but so will their spectral energy distribution. The evolution of the XUV portion of the spectrum ($1 - 2000\text{\AA}$) is particularly relevant, as photons with this energy level are the most effective at photolyzing water vapor (Watson et al. 1981), see below. Moreover, the evolution of the spectral energy distribution is important against the background that almost all land-based life on Earth

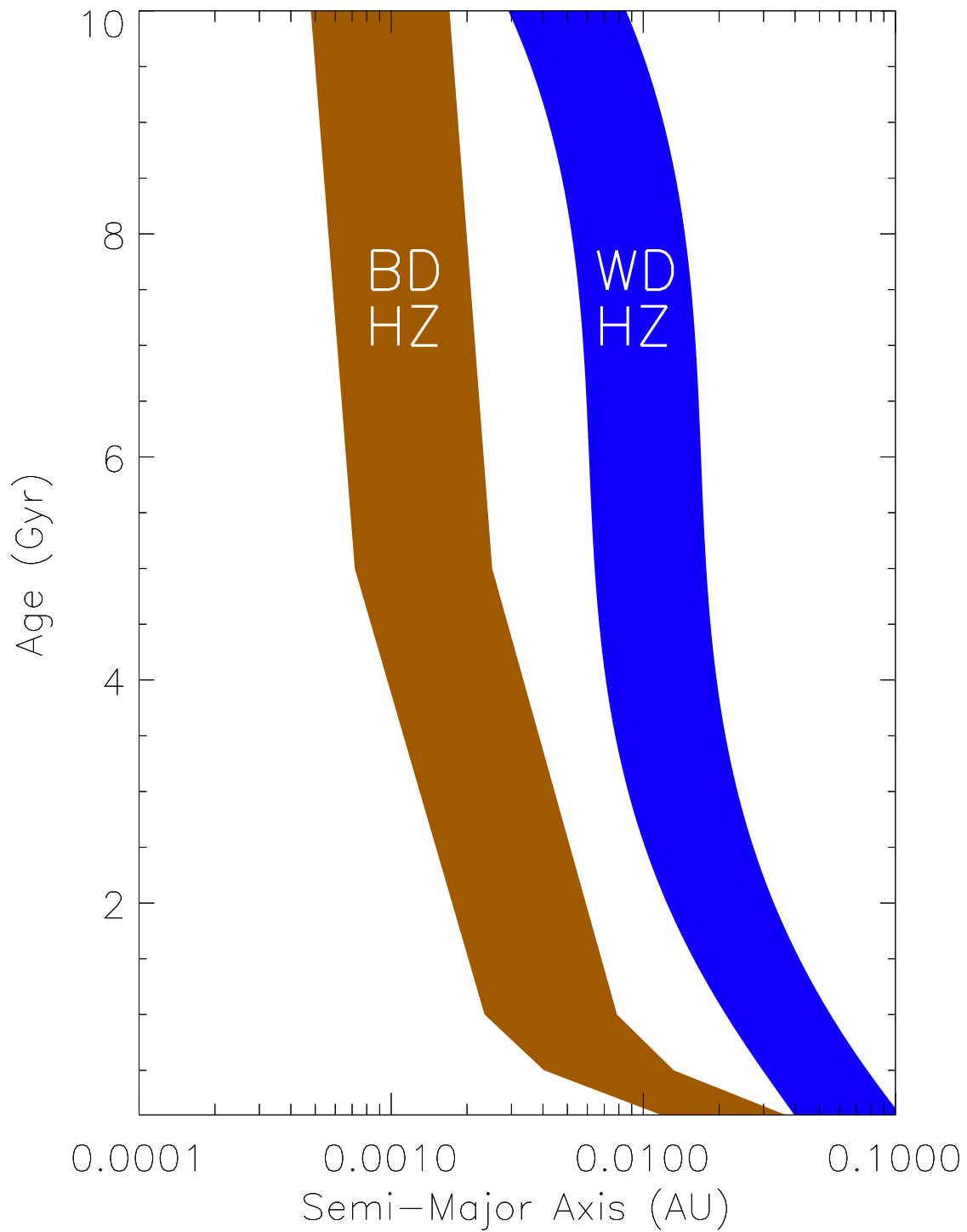


Fig. 3.— Evolution of the locations of the IHZ for a $40\ M_{\text{Jup}}$ BD (brown) and $0.06\ M_{\text{Sun}}$ WD, assuming the Baraffe et al. (2003) and Bergeron et al. (2001) cooling models, respectively.

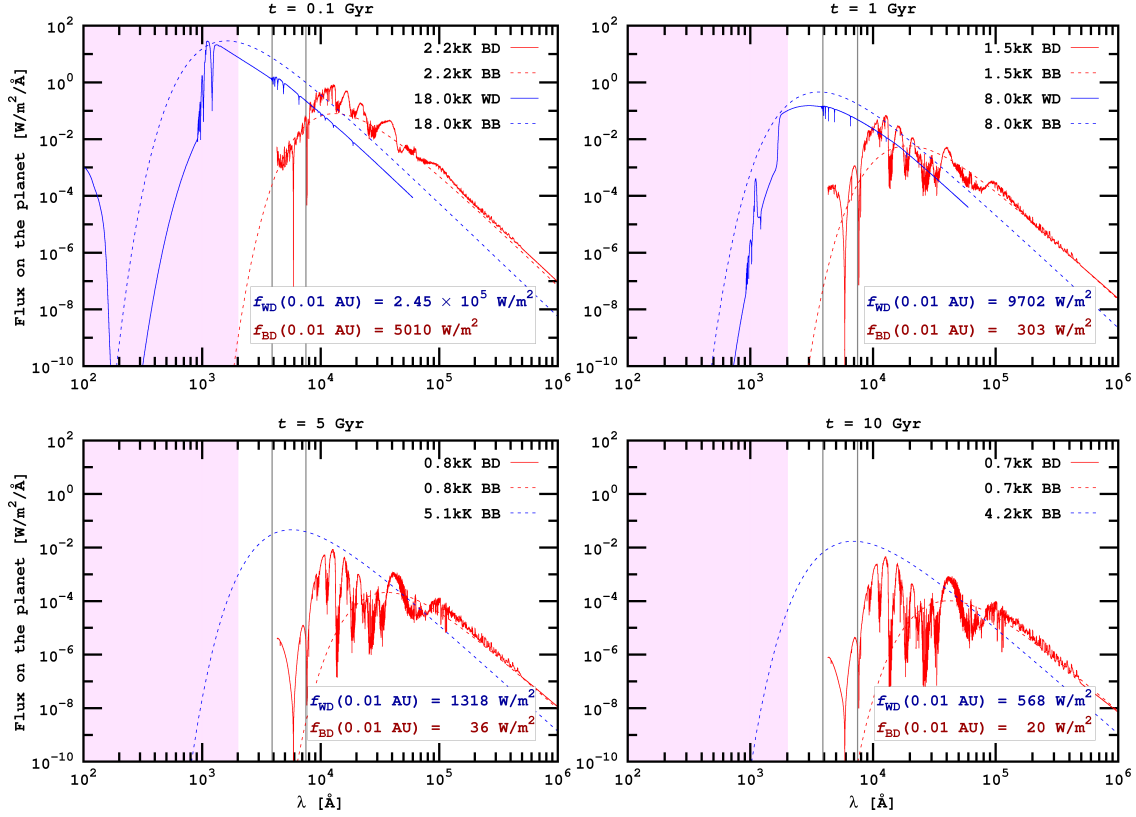


Fig. 4.— Evolution of the spectra of a $0.6 M_{\text{Sun}}$ WD and a $40 M_J$ BD. The XUV range, corresponding to those wavelengths that may photolyze water vapor, is shaded pink, while vertical lines denote the visible range used for photosynthesis on Earth. In the lower two panels we do not plot the corresponding WD spectra because such extremely low temperature models are not available. We also show the Planck curve of a WD-sized and a BD-sized black-body (BB) at 0.01 AU, respectively.

depends on photosynthesis, which operates almost exclusively in the visible range, i.e. between 400 nm and 700 nm. WD spectra typically peak in the UV, while BD emission is mainly in the infrared (IR). Thus, we shall now treat the evolution of WD and BD spectra.

We begin with the WD and consider its spectrum at 0.1, 1, 5, and 10 Gyr. Therefore, we look up the surface gravity ($\log(g_{\text{WD}})$), effective temperature ($T_{\text{eff,WD}}$), and radius (R_{WD}) of a $0.609 M_{\text{Sun}}$ WD in the $Z = 0.01$ evolution tables from Renedo et al. (2010), Z being the progenitor metallicity. We find that $\log(g_{\text{WD}})$ increases only slightly from 7.98 dex to 8.05 dex, owed to the shrinking from 0.0132 to 0.0122 R_{Sun} . Meanwhile, the effective temperature decreases from 18,400 K to 4,200 K. In Fig. 4 we plot the corresponding WD synthetic spectra (Finley et al. 1997; Koester 2010) weighted by $(R_{\text{WD}}/d)^2$, where $d = 0.01 \text{ AU}$ is the

distance of a potential planet from the WD. At 5 and 10 Gyr the WD has cooled to effective temperatures for which we do not have the synthetic spectra available. Thus, we plot the corresponding black-body profile, from which the WD would deviate less than in the upper two panels, as the WD does not emit much in the XUV.

We next consider the BD spectra corresponding to the same epochs. We choose a $40 M_{\text{Jup}}$ BD and look up the effective temperatures ($T_{\text{eff,BD}}$) and radii (R_{WD}) in Baraffe et al. (2003). We then use cloud-free BD spectral models from Burrows et al. (2006) at $T_{\text{eff,BD}} = 2, 200 \text{ K}$, $1, 500 \text{ K}$, 800 K , and 700 K ¹ and weight them with a factor $(R_{\text{BD}}/d)^2$, analogous to the procedure for the WD.

Figure 4 finally displays the WD and BD spectral flux received at a distance of 0.01 AU at 0.1, 1, 5, and 10 Gyr. We indicate the XUV range (shaded in pink) to emphasize those conditions that are most likely to remove surface and atmospheric water. While the WD spectrum at ages $> 1 \text{ Gyr}$ becomes more and more like the Sun’s, the BD departs far into the IR. The bolometric flux of the hosts (WD and BD) at a distance of 0.01 AU is given in the lower right corner of each panel. Recall that the solar constant, i.e. the Sun’s flux at 1 AU, is roughly 1400 W/m^2 .

2.5. The Desiccation Timescale

As mentioned above, XUV photons are able to liberate hydrogen atoms from terrestrial planets, a process that removes water. If the XUV flux is high enough and lasts long enough, a planet can become desiccated and inhospitable for life. Crucially, the water must be photolyzed first (by UV photons with wavelengths of 120–200 nm), in order to produce the hydrogen atoms that can escape. While WDs are initially very hot and have a peak brightness in this regime (see Fig. 4), BDs are relatively cool and UV and XUV radiation must come from emission due to activity. Observations of young BDs at these wavelengths are scarce, and hence we cannot determine the likelihood that planets interior to the HZ will in fact lose their water. In this section, we review a simple model for hydrogen loss, parametrized in terms of XUV luminosity L_{XUV} and the efficiency of converting that energy into escaping hydrogen atoms.

First, we must recognize that a wide range of water fractions are possible for terrestrial exoplanets (*e.g.* Morbidelli et al. 2000; Léger et al. 2004; Raymond et al. 2004; Bond et al. 2010). Planets with more initial water content are obviously better suited to resist total

¹available at [www.astro.princeton.edu/~sim\\$burrows](http://www.astro.princeton.edu/~sim$burrows)

desiccation, as removal requires longer time. Similarly, planets with very low water content, such as the “dry planets” proposed by (Abe et al. 2011) would desiccate more quickly than an Earth-like planet. Here we assume planets that begin with Earth’s current inventory of water, and that all that the only source of liberated hydrogen atoms in the upper atmosphere is water.

We use the atmospheric mass loss model described in Erkaev et al. (2007), which improves the standard model by Watson et al. (1981). In the Watson et al. picture, a layer in the atmosphere exists where absorption of high energy photons heats the particles to a temperature that permits escape. Photons in the X-Ray and extreme ultraviolet have the energy to drive this escape on most self-consistent atmospheres. In essence, the particles carry away the excess solar energy.

Watson et al. (1981) calculated that Venus would lose its water in 280 Myr. The actual value is probably less than that, as they were unaware that XUV emission is larger for younger stars, as the spacecraft capable of such observations, such as *ROSAT*, *EUVE*, *FUSE*, and *HST* (Ribas et al. 2005), had yet to be launched. Furthermore, their model did not consider the possibility of mass-loss through Lagrange points, or “Roche lobe overflow.” Erkaev et al. (2007) provided a slight modification to the Watson et al. (1981) model that accounts for this phenomenon on hot Jupiters. Here we use this model for a terrestrial exoplanet, which is a fundamentally different object. However, molecules above the Roche lobe should escape regardless of their composition, and hence we use the Erkaev model. We stress that the physics of atmospheric escape, especially for close-in terrestrial exoplanets, is complicated and poorly understood. In the Erkaev et al. (2007) model, mass is lost at a rate of

$$\frac{dM_p}{dt} = -\frac{\pi R_x^2 R_p \epsilon F_{XUV}}{GM_p k_{tide}}, \quad (5)$$

where R_x is the radius of the atmosphere at which the optical depth for stellar XUV photons is unity, ϵ is the efficiency of converting these photons into the kinetic energy of escaping particles, F_{XUV} is the incident flux of the photons. The parameter k_{tide} is the correction for Roche lobe overflow:

$$k_{tide} = 1 - \frac{3}{2\chi} + \frac{1}{2\chi^3} < 1, \quad (6)$$

and

$$\chi = \left(\frac{M_P}{3M_*}\right)^3 \frac{a}{R_x} \quad (7)$$

is the ratio of the “Hill radius” to the radius at the absorbing layer. From Eq. (5) it is trivial to show that

$$t_{des} = \frac{Gm_p M_H k_{tide}}{\pi R_x^2 R_p \epsilon F_{XUV}}, \quad (8)$$

where M_H is the total mass of all the hydrogen atoms that must be lost ($\sim 1.4 \times 10^{-5} M_{\text{Earth}}$ in our model, corresponding to $10^{-4} M_{\text{Earth}}$ of initial water) and assuming F_{XUV} is constant. For the cases we consider, the additional mass loss via Roche lobe overflow is $\sim 1\%$.

The values of F_{XUV} and ϵ are therefore the key parameters as they represent the magnitude and efficiency of the process. As not all the absorbed energy removes particles, ϵ must be less than 1. Observations of hot Jupiters suggest values of ϵ of 0.4 (Yelle 2004; Lammer et al. 2009; Jackson et al. 2009), while on Venus $\epsilon \sim 0.15$ (Chassefiere 1996). However, our model also requires these photons to dissociate the water molecules, hence we should expect ϵ in a water-rich atmosphere to be much less than on a hot Jupiter with a predominantly hydrogen atmosphere. For reference, using the assumptions of Watson et al. (1981), we find $\epsilon = 1.7 \times 10^{-4}$ implies $t_{des} = 280$ Myr for Venus. Note that a water-rich planet that loses its hydrogen may develop an oxygen-rich atmosphere and may be misidentified as potentially habitable. Furthermore, the destruction of O_3 by UV radiation would also be slow, and hence could lead to a “false positive” for life (Domagal-Goldman et al. 2012). This possibility requires detailed photochemical modeling for confirmation, and was beyond the scope of this study.

In Fig. 5 we show the desiccation timescale for an Earth-like planet orbiting a WD or BD at 0.01 AU. This distance is just interior to the IHZ at 100 Myr, and is therefore a critical location for a planet to experience sustained habitability in the future. For most young WDs, the peak brightness lies in the XUV, and the total luminosity is $> 10^{-3} L_{\text{Sun}}$. Thus, their planets are in an environment characterized by the top portion of the graph. In order to avoid desiccation, those planets must have $\epsilon < 10^{-6}$. This is a very small value, and we expect that planets initially interior to the IHZ will be desiccated by the time it arrives.

The situation for BD planets is difficult to assess at present. The two steps of photolysis and escape require knowledge of the evolution of UV and XUV emission, which is largely unknown at present. The cool temperatures of BDs suggest that photolysis may be the limiting step in the desiccation process, as the BD photospheres may be too cool to emit enough UV radiation to drive desiccation. Assuming that water molecules can be destroyed, it is unclear if the XUV emission is large enough to drive mass loss, too. We can appeal to low-mass M dwarfs for guidance and extrapolate the results of Pizzolato et al. (2003) to the BD realm. They estimated the “saturation level” of XUV radiation, which is the largest amount of XUV luminosity as a fraction of total luminosity, observed in stars. They find that for stars with masses in the range $0.22 - 0.6 M_{\text{Sun}}$ that the XUV emission never represents more than 10^{-3} of the total. At 100 Myr, BDs are expected to have luminosities near $10^{-4} L_{\text{Sun}}$, and hence their XUV flux should be less than $10^{-7} L_{\text{Sun}}$. In order for a planet initially at 0.01 AU from a BD to avoid desiccation, $\epsilon < 5 \times 10^{-3}$. We caution that

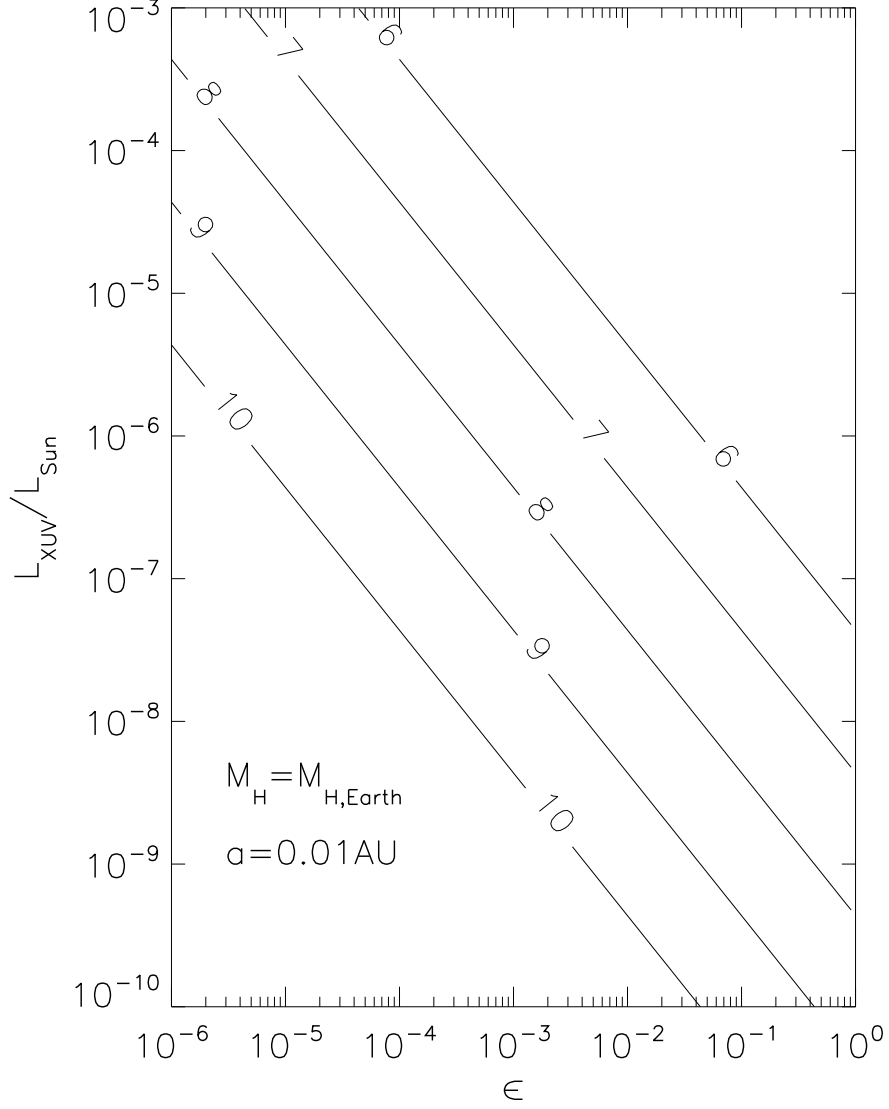


Fig. 5.— Desiccation timescale for an Earth-like planet orbiting a BD or WD at 0.01 AU. Contour lines represent the logarithm of the time for the Earth’s inventory of hydrogen to be lost, *i.e.* the planet’s mass of hydrogen in water M_H is equal to the Earth’s $M_{\text{H,EARTH}}$.

BD interiors are expected to be fully convective, while stars in the above mass range are not, and hence the stars in Pizzolato et al. (2003) may not be analogous to BDs. A survey of XUV emission from a large sample of BDs is sorely needed to address this aspect of planetary habitability, but will be very challenging, even from space. On the other hand, spectral characterization of atmospheres in the IHZs of older BDs could provide the tightest constraints on the early high-energy emission of BDs.

2.6. Tidal Effects

We use the two tidal models described in Heller et al. (2011), and the numerical methods described in (Barnes et al. 2012), see also (Ferraz-Mello et al. 2008; Greenberg 2009; Leconte et al. 2010). These models are qualitatively different, but widely used in astrophysics and planetary science. They both assume that the tidal bulge raised on a body lags behind the apparent position of a perturber and that the shape of the deformed body can be adequately modeled as a superposition of surface waves. One, which we call the “constant time lag” (CTL) model, assumes that the time between the passage of the perturber and the passage of the tidal bulge is constant. The tidal effects are encapsulated in the product of the “tidal time lag” τ and the second-order tidal Love number k_2 . The other model, which we call the “constant phase lag” (CPL) model, assumes that the angle between the lines connecting the centers of the two bodies and the center of the deformed body to the bulge is constant. The tidal effects in this model lie in the quotient of the “tidal quality factor” Q and k_2 . The tidal time lag and quality factor essentially measure how effectively energy is dissipated inside a body.

As in Barnes et al. (2012), we assume the planets are Earth-like with $\tau = 640$ s or $Q = 10$ (Lambeck 1977; Yoder 1995). The tidal heating scales linearly with these parameters and as semi-major axis a to the -7.5, eccentricity e squared, obliquity ψ_p squared and spin frequency ω_p squared, (see Barnes et al. 2012). The heat flux F through the surface is critical for surface life, and is also a measure of how geophysical processes transport energy. Martian tectonics is believed to have shut down at a heat flux of 0.04 W m^{-2} (Williams et al. 1997), The Earth’s heat flux, due to non-tidal processes, is 0.08 W m^{-2} (Pollack et al. 1993), Io’s heat flux due to tidal heating, is 2 W m^{-2} (Strom et al. 1979; Veeder et al. 1994), and the limit to trigger a runaway greenhouse is $F_{crit} = 300 \text{ W m}^{-2}$ (Pierrehumbert 2010). We will use these limits to explore the habitability of planets orbiting WDs and BDs (see below). We shall thereby keep in mind that these values are not natural or material constants but depend strongly on a planet’s composition, mass, and age.

The tidal Q of WDs is poorly constrained. Recently, Piro (2011) used the luminosities

of an eclipsing He-C/O WD binary to place limits on the Q values of the two companions. He found the former has $Q < 7 \times 10^{10}$ and the latter has $Q < 2 \times 10^7$. Unfortunately these are relatively rare classes of WDs, as 80% are classified as H WDs. These values are probably larger than for solar-type stars (Jackson et al. 2009), and predict little dissipation in the WD from the terrestrial planet. Furthermore, these values preclude the possibility that the planet’s orbit could tidally decay at a rate that allows it to remain in the IHZ as the WD cools. At 100 Myr, the IHZ is at ~ 0.05 AU, and the tide on the WD is negligible. This assumes the WD rotation period is longer than the orbital period, which may not be the case. The rotation rates of WDs can span a wide range, from seconds to years, but should initially rotate with periods longer than one day (Kawaler 2004; Boshkayev et al. 2012).

Tidal processes in BDs are also relatively unexplored. Heller et al. (2010) used the CPL and CTL models to explore the range of tidal heating available in the eclipsing BD binary pair 2MASS J05352184-0546085 (Stassun et al. 2006). This study indicates that tidal heating can be significant in BDs. Tidal evolution of BDs orbiting main sequence stars has also been calculated for a few cases, (*e.g.* Fleming et al. 2010; Lee et al. 2011), but tidal dissipation in BDs remains poorly constrained. Here we assume $Q = 10^6$, which is a reasonable estimate based on those prior studies. We use the radius values as a function of time given in Baraffe et al. (2003).

2.7. Classifying Planets by Radiative and Tidal Heat

Different levels of insolation and tidal heat can be used to devise a classification scheme for terrestrial exoplanets orbiting in and around the IHZ. Here we propose categories that are relevant for the discussions in §§ 3–4. The categories are defined by the origin and total amount of upward energy flux at the planetary surface. That due to orbit-averaged insolation, and assuming efficient energy redistribution, is

$$F_{insol} = \frac{L_p}{16\pi a^2 \sqrt{1 - e^2}} (1 - A), \quad (9)$$

where L_p is the primary’s luminosity, a is semi-major axis, e is eccentricity, and A is the planetary albedo. In addition to this heating, there is also an energy flux resulting from the cooling of the planetary interior. Three sources are known to be possible: radioactive decay, latent heat of formation, and tides. Here we will focus on the tidal heat. The amount of radioactive and latent heat is very difficult to calculate from observations, whereas the tidal heat can at least be scaled by a single parameter. When the tidal heat drops below a level that is geophysically interesting, then we will assume that the planet’s interior behaves like the Earth, which has a heat flux of 0.08 W m^{-2} , of which a negligible fraction is due to

tides. We are therefore assuming that in the absence of tidal heating, the planetary interior behaves like the Earth’s. The flux due to tides is F_{tide} (see Barnes et al. 2012). The sum of F_{insol} and F_{tide} is F_{tot} .

Three Venus-like planets are possible. An “Insolation Venus” is a planet that receives enough stellar radiation to trigger a moist or runaway greenhouse. A “Tidal Venus” is a planet whose tidal heat flux exceeds the runaway greenhouse flux, $F_{tide} \geq F_{crit}$. Finally, “Tidal-Insolation Venuses” are planets with $F_{tide} < F_{crit}$ and $F_{insol} < F_{crit}$, but $F_{tide} + F_{insol} \geq F_{crit}$.

“Super-Ios” are worlds that experience tidal heating as large or larger than Io’s ($F_{tide} \gtrsim 2 \text{ W m}^{-2}$), but less than F_{crit} (Jackson et al. 2008), see also Barnes et al. (2009b,a). We assume that the dissipation in the interior determines the onset of Io-like volcanism and that tidal dissipation in the interior is 10 times less effective than in an ocean. Therefore, we determine the Super-Io boundary using $\tau = 64 \text{ s}$ or $Q = 100$.

In the IHZ are two types of habitable planets. Planets with $2 \text{ W m}^{-2} \geq F_{tide} \geq 0.04 \text{ W m}^{-2}$ are “Tidal Earths.” Those planets with $F_{tide} < 0.04 \text{ W m}^{-2}$ are “Earth Twins” as they are in the IHZ and receive negligible tidal heating.

Planets exterior to the IHZ and with $2 < F_{tide} < 0.04 \text{ W m}^{-2}$ are labeled “Super-Europas,” while those with $F_{tide} < 0.04 \text{ W m}^{-2}$ are “Snowballs.” While both may possess layers of sub-surface water, these environments are not detectable across interstellar distances.

3. Planets Orbiting White Dwarfs

3.1. $0.6 \text{ M}_{\text{Sun}}$ White Dwarfs

The luminosity of a $0.6 \text{ M}_{\text{Sun}}$ WD is $\sim 10^{-3} \text{ L}_{\text{Sun}}$ (Bergeron et al. 2001), and hence the IHZ is located at $\sim 0.01 \text{ AU}$ (Agol 2011b). In Fig. 6 we show the planetary classifications of $1 \text{ M}_{\text{Earth}}$ planets in orbit around a $0.6 \text{ M}_{\text{Sun}}$ WD at 4 different times, assuming the cooling model derived in § 2. Here we assume that the planets rotate with the equilibrium period and with no obliquity. Note the low values of eccentricity, a testament to the power of tides in these systems.

At 100 Myr, the WD is very hot, $\sim 10^4 \text{ K}$. This effective temperature is outside the range considered by Selsis et al. (2007), and hence in order to obtain a close match between the 50% cloud cover boundary of Selsis et al. (2007) and the runaway greenhouse limit of Pierrehumbert (2010) we set the planetary albedo to 0.87. (For the later times we used

$A = 0.5$.) Even at that large value, the inner boundary of the IHZ does not align with Pierrehumbert’s prediction. Earth Twins require $e \lesssim 0.01$.

From 0.1 – 1 Gyr, the WD cools rapidly, see Fig. 1, and afterward the IHZ has moved in by 50%. Tidal effects desiccate more of the IHZ at “large” eccentricity, and much is in the Tidal Earth regime. However at 1 Gyr, most of the IHZ below $e = 0.01$ still appears habitable.

By 5 Gyr, however, (lower left panel), even at very low eccentricities, most planets in the IHZ will experience strong tidal effects. At $e = 10^{-5}$, the inner edge is experiencing at least Tidal Earth conditions and Earth Twins must be at the outer edge and with $e < 10^{-4}$. Agol (2011b) identified 4 – 7 Gyr as a “sweet spot” for planets around WDs, as the cooling levels off, see § 2, but in order to be habitable, candidate planets require very low eccentricities in order to avoid a tidal greenhouse. Note that at $a = 0.01$ AU and $e = 10^{-4}$ the difference between closest and farthest approach from the host is $2ae = 300$ km, or about 5% the radius of the Earth.

At 10 Gyr (lower right panel), the situation has continued to deteriorate for habitable planets. Not only has the width of the IHZ shrunk considerably, but Earth Twins are only possible if $e < 10^{-5}$! Habitability at this stage probably requires a system consisting of one WD and one planet, as additional planet mass companions can raise e above this threshold, see below and Barnes et al. (2010). As with CoRoT-7 b, the galactic tide or passing stars cannot pump e to this “large” value (Barnes et al. 2010).

Tides on planets orbiting WDs are a strong constraint on habitability, but are less important than the WD’s cooling. Consider the left panels of Fig. 6. In the bottom panel, the IHZ lines up with Insolation Venus (purple) and Tidal Venus (red) regions of the upper panel. Therefore, planets located in the 5 Gyr IHZ were interior to the 0.1 Gyr IHZ. Furthermore, young WDs are very hot and emit substantial energy in the XUV wavelengths that photolyze H_2O . As $0.1 \text{ Gyr} \sim t_{des}$, we expect planets in the 5 Gyr IHZ to have been desiccated well before the IHZ reaches them. In other words, habitability requires special circumstances that override the standard picture of habitability. Unfortunately tidal decay of the (circular) orbit is unlikely, as the tidal Q (τ) is probably very large (small) for WDs (Agol 2011b; Prodan & Murray 2012). Therefore, planets orbiting hydrogen WDs will not spiral in, and cannot keep pace with the shrinking IHZ.

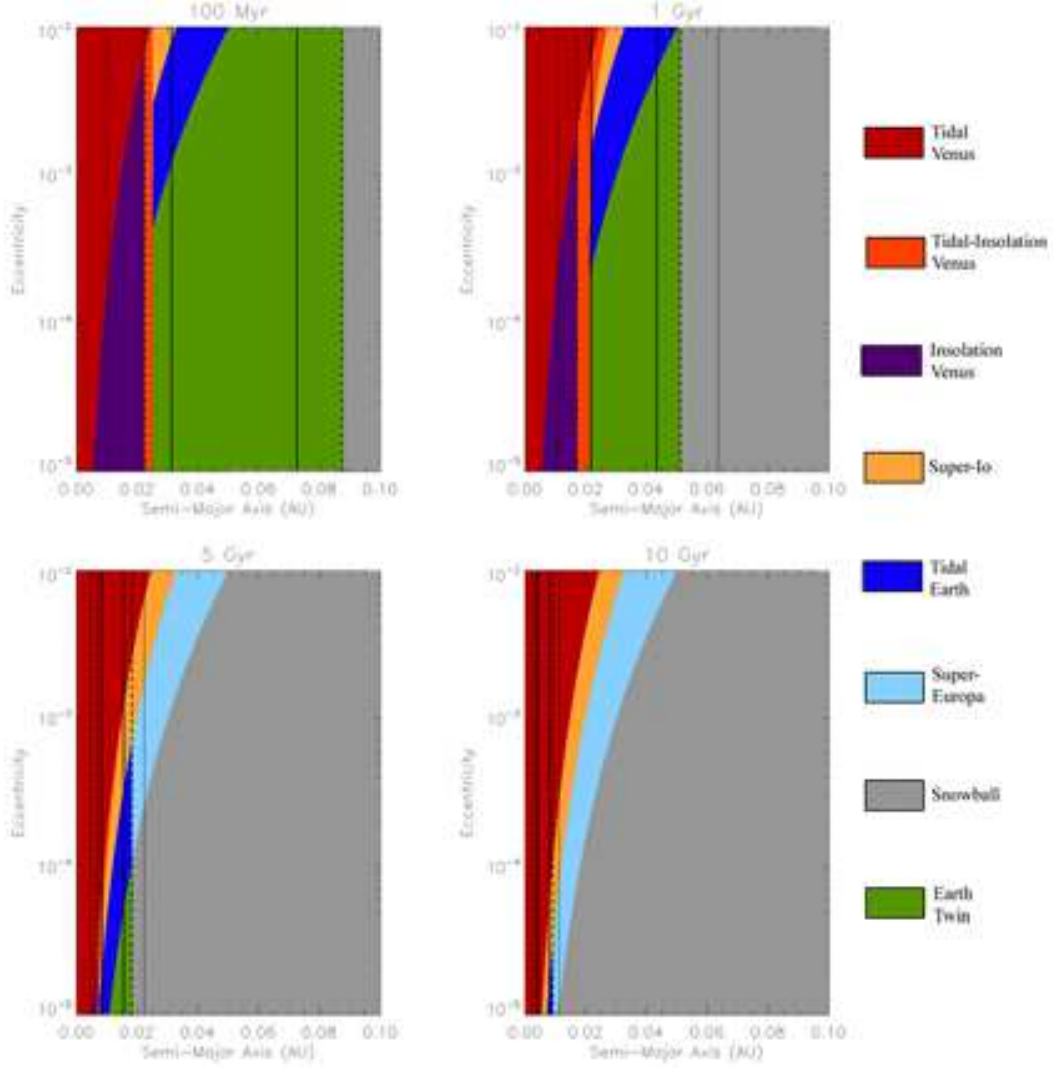


Fig. 6.— Planetary classifications for a tidally-locked $1 M_{\text{Earth}}$ planet with no obliquity in orbit about a $0.6 M_{\text{Sun}}$ WD. As WDs cool significantly with time, we show the phases and IHZ as a function of time, from 100 Myr (top left) to 10 Gyr (bottom right).

3.2. KOI 55

Two planet candidates have recently been proposed that orbit an extreme horizontal branch star, an astrophysical object that will shortly transition to a WD. These candidates were found with the *Kepler* spacecraft and are designated KOI 55.01 and KOI 55.02 (Charpinet et al. 2011). The stellar mass is $0.5 M_{\text{Sun}}$, and the two planets’ radii are 0.76 and $0.87 R_{\text{Earth}}$. If Earth-like in composition and structure, these planets have masses of 0.41 and $0.63 M_{\text{Earth}}$, respectively (Sotin et al. 2007). If these candidates are real, then they will orbit a WD and hence could become habitable. Moreover, their detection implies that these planets may be typical of those that orbit WDs. In this subsection we consider the future habitability of these two objects.

The two candidates have semi-major axes of 0.006 and 0.0076 AU. The outer planet, KOI 55.02, therefore falls in the IHZ during the crystallization epoch from 4–7 Gyr. The primary currently has a temperature of $27,700$ K and therefore emits strongly in the XUV and X-Ray spectral regimes (see Fig. 3, upper left panel). These planets are therefore roasting, and likely losing their water (if they had any). Hence, both objects are in danger of sterilization due to irradiation now, and are unlikely to become habitable later. Furthermore, this extremely high temperature suggests our nominal value for t_{des} may be too high.

There is also a danger that perturbations between the two planets (which may be in a 3:2 resonance) may maintain a large enough eccentricity ($\gtrsim 10^{-4}$) to sustain a tidal greenhouse. To test for this possibility we ran two numerical simulations of the gravitational perturbations between the planets using HNBODY². The first case used the nominal values from Charpinet et al. (2011), and the second forced the two planets into an exact 3:2 mean motion resonance by pushing the outer planet’s period to 8.64 hours. For the former, the eccentricity of KOI 55.02 oscillated between 5×10^{-6} and 5×10^{-5} . This range places the planet in the Tidal Earth or Earth Twin regime. For the latter case, the resonance perturbs the eccentricity more strongly, and it varies between 10^{-4} and 10^{-3} . These values are in the Tidal Venus range and the planet would not be habitable. However, given the strong tidal forces in this region, these ranges are probably maximum values. Nonetheless the future habitability of these two planet candidates seems unlikely.

²Publicly available at <http://janus.astro.umd.edu/HNBODY>

4. Planets Orbiting Brown Dwarfs

As in Bolmont et al. (2011), we consider a $0.04 M_{\text{Sun}}$ BD and employ the theoretical cooling and contraction models of Baraffe et al. (2003), to calculate IHZ boundaries. Here we extend the results of Selsis et al. (2007) to the luminosity and temperatures of BDs, which give similar limits as in Bolmont et al. (2011). In this case, we use the CPL model with a continuum of rotation states (see Barnes et al. 2012, App. D.3) to determine F_{tide} , and set the BD’s obliquity to 0 and its rotation period to 1 day (note that these values do not affect the tidal heating in the planet).

In Fig. 7 we show the boundaries for planetary classes for a $1 M_{\text{Earth}}$ planet after 100 Myr, 1 Gyr, 5 Gyr and 10 Gyr. Note that the scales of the axes change for each panel. At 100 Myr, *i.e.* t_{des} , planets in the IHZ with $e > 0.01$ may be in a Tidal Venus state. Also note that our model predicts that all planets interior to 0.016 AU will have lost their water. At 1 Gyr planets must have $e < 5 \times 10^{-5}$ to avoid a tidal greenhouse, but at this point, the IHZ has moved into a region in which all water should already have been lost. To avoid a Tidal Venus state at 5 and 10 Gyr, eccentricities must be less than 10^{-6} and 10^{-7} , respectively. Therefore, even if a planet could maintain its water inventory until the IHZ reached its orbit, a planet must have an extremely circular orbit to avoid catastrophic tidal heating. Also note that the Roche lobe, the distance where a planet is in danger of being torn apart by tides, lies at $\sim 3 \times 10^{-3}$ AU (Andreeshchev & Scalo 2004; Bolmont et al. 2011), further limiting habitability.

Bolmont et al. (2011) point out that tides will tend to push planets out, in an analogous manner as the Moon recedes from the Earth. Therefore, as the planets move out and the IHZ moves in, the residence time in the IHZ can be quite short. They considered the example of a planet that begins at 9×10^{-3} AU and find that planets between 0.1 and $10 M_{\text{Earth}}$ will require at least 50 Myr to reach the IHZ. As this time is of order t_{des} , the key limit to habitability may be that those planets will have already lost their water, rather than the relatively short time the planets spend in the IHZ. However, not enough is known about activity on young BDs to accurately determine the threat of photolysis and hydrogen escape.

5. Conclusions

Planets orbiting WDs and BDs suffer a number of critical habitability issues, such as strong tidal heating, water loss due to bombardment by high energy photons, a spectral energy distribution very different from the Sun’s, and a cooling primary. Here we have

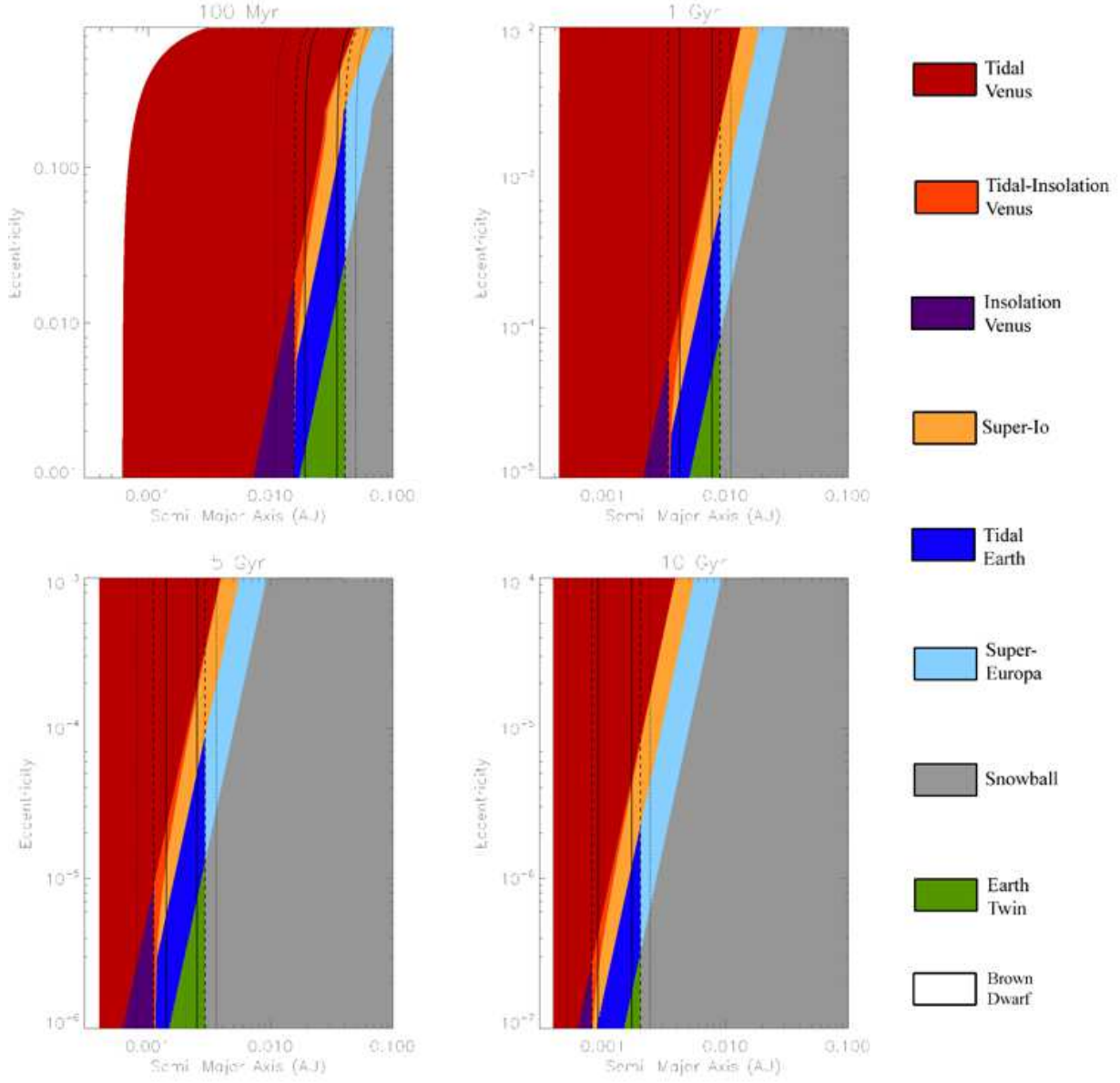


Fig. 7.— Planetary classifications for a tidally-locked $1 M_{\text{Earth}}$ planet with no obliquity, in orbit about a $0.04 M_{\text{Sun}}$ brown dwarf at 100 Myr (top left), 1 Gyr (top right), 5 Gyr (bottom left), and 10 Gyr (bottom right). White regions correspond to orbits that intersect the BD.

outlined how dire the situation is for these types of planets, using simple but standard models of the IHZ, tidal heating, and cooling rates. We conclude that WDs are even less likely to support habitable planets than BDs due to the former’s stronger XUV emission.

As the luminosities of WDs and BDs change dramatically with time, see Figs. 1–3, the IHZ moves inward. Planets interior to the IHZ experience a desiccating greenhouse phase for times longer than t_{des} due to insolation and hence lose their water before the IHZ reaches their orbit, and are hence uninhabitable. This possibility is more likely for WDs than BDs as the former’s peak radiation lies in the near UV, while constraints on the latter’s emission are difficult to obtain. New data on the duration and strength of BD activity are sorely needed. However, even if the spectral energy distribution of the host does not remove the hydrogen, the orbital eccentricities must remain very low in order to avoid a tidal greenhouse.

Once a planet is in the IHZ, there are four requirements for habitability: 1) The eccentricity must be low enough to avoid a tidal greenhouse, 2) a reservoir of water must survive the desiccating greenhouse phase, perhaps trapped in the mantle, 3) a mechanism must exist to draw down CO_2 and quench the moist greenhouse, and 4) a (possibly different) mechanism must release the water reservoir to the surface. Currently, no phenomena are known that can satisfy all four of these constraints.

On the other hand, the possibility exists that the planet could arrive in the IHZ from a further distance (see *e.g.* Agol 2011a). For example, if a more distant and massive companion is present, gravitational perturbations could excite the planet’s eccentricity such that the pericenter distance is close enough for tides to circularize the orbit. Then the planet could arrive in the IHZ in a circular orbit after tidal circularization (Nagasawa et al. 2008). Alternatively, a late-stage planet-planet scattering event could move a terrestrial planet from a more distant orbit to the IHZ. Recent observations suggest that planetary systems with 2:1 mean motion resonances are younger than average, suggesting they break apart as they age (Koriski & Zucker 2011). In both these scenarios, the planet still has to contend with large eccentricities, and hence tidal heating could still sterilize the surface. Additionally, the planet would have to break out of its frozen state, and it is unclear if such “cold starts” are possible (Kasting et al. 1993). Unfortunately these sorts of histories are nearly impossible to recognize from a planet on a circular orbit, and hence we should not expect to be able to determine if a planet arrived in the IHZ without experiencing desiccating conditions. Nonetheless, future work should determine if planets can still be habitable after an extended time in the runaway greenhouse, and the likelihood that planets orbiting WDs and BDs can migrate long after their formation.

Planets are complex objects and we hesitate to rule out habitability, but planets orbiting BDs and WDs face a difficult path to habitability. On the other hand, as pointed out by

Agol (2011b), the signals for some of these objects could be very easily detected. If a planet is found in the IHZ of a cooling primary, follow-up observations should still be carried out. Regardless of their habitability, terrestrial planets found around these objects will provide fundamentally new insight into planet formation, and hence into the extent of life in the universe.

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